



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(54) Title: A SYSTEM AND METHOD FOR COMMAND AND CONTROL (54) Titre: SYSTEME ET METHODE DE COMMANDE ET DE CONTROLE		
(57) Abstract <p>The present invention performs adaptive and robust command and control by identifying operation sequences that are outcome determinative or polyfunctional.</p> (57) Abrégé <p>La présente invention concerne un système adaptatif de commande et de contrôle consistant à identifier des séquences opérationnelles qui sont déterminantes pour l'issue de l'opération ou qui sont plurifonctionnelles.</p>		

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(21) International Application Number: PCT/US99/25398 (22) International Filing Date: 29 October 1999 (29.10.99) (30) Priority Data: 60/106,022 29 October 1998 (29.10.98) US (71) Applicant (for all designated States except US): BIOS GROUP LP [US/US]; 317 Pasco de Peralta, Santa Fe, NM 87501 (US). (72) Inventor; and (75) Inventor/Applicant (for US only): KAUFFMAN, Stuart, A. [US/US]; 1811 S. Camino Cruz Blanco, Santa Fe, NM 87505 (US). (74) Agents: MORRIS, Francis, E. et al.; Pennie & Edmonds LLP, 1155 Avenue of the Americas, New York, NY 10036 (US).		(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG). Published <i>With international search report.</i>
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Description

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A SYSTEM AND METHOD FOR
COMMAND AND CONTROL

FIELD OF THE INVENTION

The present invention relates generally to a method for command and control. More specifically, the present invention performs adaptive and robust command and control by identifying operation sequences that are outcome determinative or polyfunctional.

BACKGROUND

Previous research has applied techniques involving technology graphs and landscape representation to operations management as described in U.S. Patent Application 09/345,441, the contents of which are herein incorporated by reference. But previous research has not applied these techniques to command and control problems.

Accordingly, there exists a need to perform adaptive and robust command and control using technology graphs and landscape representations.

SUMMARY OF THE INVENTION

The present invention presents a system and method that performs adaptive and robust command and control by identifying operation sequences that are outcome determinative or polyfunctional.

It is an aspect of the present invention to present a method for performing command and control comprising the steps of:

defining a plurality of subtasks;
determining one or more of said subtasks that causally effect one or more fundamental outcomes wherein said fundamental outcomes comprise winning outcomes and losing outcomes; and

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determining values for said order parameters to
achieve a winning one of said fundamental outcomes.

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5 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

10 The present invention will be explained in the context of a military battlefield consisting of Red and Blue forces. However, as is known to persons of ordinary skill in the art, the techniques of the present invention are applicable to any problems using command and control.

15 The present invention addresses three approaches to command and control. First, in the joint strategy spaces of Red and Blue forces in the defined battle space, are there a modest number of alternative fundamental outcomes of the battle? If so, can we define "phase volumes" in strategy space corresponding to each of these different outcomes? Inside of each such volume, the combined Red and Blue strategies lead to the same fundamental outcome. Crossing 20 between phase volumes to neighboring different fundamental outcomes corresponds to "phase transitions" in the physicist's sense. Physicists speak of "order parameters" - the causally effective collective conditions that define the phase transition. For example, in a outcome. Crossing between 25 phase volumes to neighboring different fundamental outcomes corresponds to "phase transitions" in the physicist's sense. Physicists speak of "order parameters" - the causally effective collective conditions that define the phase transition. For example, in a ferromagnet, the order 30 parameter is the number of magnetic dipoles, or spins pointing in the same direction. Since spins "want" to point in the same direction, when the thermalizing effect of temperature is lowered, the collective reduction in energy in spin alignments overcomes the randomizing forces of 35 thermalization, and magnetization spontaneously occurs. In a similar way, we define "collective tasks and subtasks" which must be achieved to remain in a given phase volume in battle space to assure a positive outcome, or which must be transgressed to exit a "losing" phase volume battle outcome 40 and transition into a "winning" volume. The first approach chooses sequences of subtasks and alternative sets of 45

5 subtasks which collectively might assure that the battle has the desired outcome.

10 The second approach to command and control concerns robust strategic and tactical operations. The approach brings
5 substantial new tools to bear that yield useful understanding and supplies decision support tools for actual military operations. The fundamental ideas rest on the new concept of a "technology graph" of all the alternative pathways to
15 achieve sets of tasks, as well as sets of neighboring alternative tasks, leading to one or a set of ultimate goals. Technology graphs were explained in U.S. application 09/345,441, filed July 1, 1999, the contents of which are
20 herein incorporated by reference. As explained in that patent application, the technology graph is a principled
15 mathematical framework in which to analyze robust pathways to a single objective, or a set of alternative objectives. Here "robust" is quantitatively defined in terms of the number of
25 alternative nearby pathways to each task, where a large number of alternatives implies that failure along any one
20 segment of any pathway is readily overcome by graceful deviation to a neighboring pathway. In consideration of a set
30 of alternative tasks or objectives, a related sense of robust identifies the node subtasks that are optimally on the pathways to multiple alternative objectives and allow
25 graceful redeployment to achieve changing objectives.

35 The second approach also concerns the fundamental idea of a technology graph, a second major concept concerns a generic phase transition in problem solvability from a "living dead" regime to a "survivable" regime in the face of
40 a coevolving enemy force. The living dead regime generically occurs when we attempt to be too efficient. The survivable regime arises when we relax our efficiency requirements just enough to reduce conflicting constraints in the problem space to a point beyond the phase transition. This phase transition
45 is quantifiable, has been demonstrated in several cases, and leads to the clear implication that we should operate in the survivable regime sufficiently near the living dead regime to

5 assure efficiency, yet far enough back from the phase
transition in the survivable regime to withstand attrition
and uncertainties due to the fog of war.

10 The third approach of the present invention concerns
5 optimal command and control structures, command by direction,
by plan, or by intent, in the face of the need for adaptive,
flexible, robust, survivable operations. Recent results in
15 "complexity" exhibit clear quantitative cases in which
centralized decision making is best, and clear alternative
10 cases in which optimal performance is achieved by distributed
decision making in modular units which each make decisions to
optimize local goals regardless of the effects those
20 decisions may have of neighboring modules with different
goals. The reason such "selfish" modular decision making can
15 be more successful than centralized command is that the
"selfish" units ignore some of the conflicting constraints in
the entire problem space. The collective effect is that the
25 system avoids becoming trapped on very poor compromise
solutions and can jointly "explore" its space of operations
20 more widely. In specific cases, it now appears that optimal
collective decision making in the face of complex conflicting
constraints occurs at a phase transition between an ordered
30 regime and a chaotic regime. One internal signature of such a
collectively adaptive system is that a power law distribution
25 of many small and few large "avalanches" of change propagate
through adapting organization. The present invention uses
35 model battlespace and agent based models of Red and Blue
forces to assess alternative ways to achieve flexible
adaptive command and control.

30 It is important to stress that the new criteria above
for distributed command and control - the avoidance of poor
compromises, is a new concept, unrelated to the difficulties
of command by direction when the battlespace is only
40 partially known to the commander, and unrelated to the
difficulties of direction by plan when plans appear to many
35 to be generically fragile and non-robust. Rather, the core
issue concerns organization for the capacity to adapt rapidly

5 and robustly while operating in the survivable regime noted above.

10 A central feature of the approaches of the present invention is a "crude look at the whole". By using agent based models of simplified battle spaces, we can examine the interrelations between opposing force structures and capabilities, strategy spaces with respect to operations, the consequent requirements for intelligence which feedback and guide the evolving battle, the robustness of operations and 15 the emergence of "unintended consequences" as our adaptive agents explore their strategy spaces. The unintended consequences will find the "chinks" in Red and Blue team strategies. If we can succeed in our first objective of finding alternative phase volumes in the strategy space of 20 the battlespace, these chinks help define the boundaries between volumes where Red force and Blue force win.

25 As previously mentioned, the present invention will be explained in the context of a military battlefield consisting of Red and Blue forces. The exemplary battlefield model consists of two political domains with a boundary, both 30 bordering an oceanfront. Red forces occupy the northern domain. Blue forces are located in the southern domain. The purpose of blue force is to prevent any incursion across the boundary into its territory. Red's objective is to take over 35 Blue territory. The exemplary battlefield model further includes battle agents in the air, (A/C Helo), land (Tanks, MSLs SAM), and sea (Ships MSLs SAM) for Blue and Red forces. Red and blue forces have biological and chemical weapons as well. Agent characteristics include reach (range and speed), 40 and lethality. Intelligence assets include satellites, UAVs, SIGINT. Command and control structures. Targets air/land/sea, C2 facilities, wpns storage, POL, infrastructure (bridges etc.) The measures of effectiveness include time, attrition and cost.

45 35 The battlefield model includes agent based models of entire battlespace to different desired levels of disaggregation. More generally, agents can represent

5 battalions, corps, divisions, down to individual soldiers. In
general, agents are endowed with a set of "genetic
characteristics". These include the fundamental
10 characterization of the "primitive moves" each human or
battle agent can make. Thus, tanks have features of speed,
range, gas utilization, firepower, accuracy, vulnerability
profiles. A commander of a tank corp might have
characteristics concerning propensities to attack or retreat
15 in definable contexts (for example as defined by "doctrine"
in one or more default hierarchies), experience level
(modeled by the extent of off line simulation the commander
can "run" to assess and make decisions), a prioritized set of
20 targets, information about the possible primitive and
compound actions of friendly and enemy agents.

15 However, as is known to persons of ordinary skill in the
art, the techniques of the present invention are not
dependent on any particular model because they are applicable
25 to any problems using command and control.

We begin by discussing the second approach of the
20 present invention involving the "Technology Graph" of
possible sequences of operations. The technology graph is a
new mathematical framework to consider robust operations.

30 Without limitation, the technology graph will be
explained in the context of a "Lego world". Consider a set of
25 primitive Lego parts, 1x1, 1x2, 1x3, 1x4 blocks, and
primitive operations - attaching two blocks or separating two
35 blocks. Define a "founder set" with a very large number of
primitive parts. Consider in Rank 1, all possible unique
objects that can be constructed from the founder set in a
30 single move 2 has all unique Lego objects that can be
constructed in two steps, rank 3 has all unique Lego objects
40 that can be constructed in three steps, etc. A technology
graph is a set of objects and transformations among those
objects. We can, if we wish, define specific machines,
45 themselves made of Lego objects, that carry out each of the
different primitive lego construction or disassembly
operations. In general, the technology graph is infinite.

5 A core use of the technology graph is to define
alternative useful senses of "robustly constructable, or
robustly achievable. In the case of Lego, suppose a specific
Lego house is first constructed in 20 steps, hence is in rank
10 20. It might be the case that there is but one pathway from
5 the founder set to the house in 20 steps, or there may be
thousands of alternative pathways to the house in 20 steps.
In the latter case, we say that the house is robustly
15 constructable. Intuitively, if there are many alternative
10 pathways, then it will be difficult to block assembly of the
house in 20 steps, for blockage of one pathway at a step can
typically be gracefully overcome by deviation to a nearby
construction pathway. A closely related notion of robustly
20 constructable or achievable is to ask how the number of ways
15 of making the house increase after the first occasion it can
be made, hence in 21, 22, 23, etc steps. Perhaps the number
of ways increases slowly, perhaps hyperexponentially. In the
25 latter case, it may be very worth while constructing the
object in 22 steps because so many redundant pathways exist
20 that blocking construction of the house by substantial
attrition of parts and machines cannot be achieved.
Construction is robust.

30 A related but different sense of robustly constructable
considers a set of final objects, or objectives or tasks.
25 Consider, then, a lego house and a lego house with a chimney.
Intuitively, a family of objects, objectives, or tasks, is
35 robustly achievable if pathways to one of the objects are
well on the way to others of the objects. Thus, consider a
specific way to make the house and ask what must be done from
30 that pathway to divert to a house with a chimney. Perhaps the
chimney can simply be added. More generally, the house must
be deconstructed to some stage, then rebuilt to include the
chimney. Consider for each way to build the house, the branch
point to the house with the chimney. These branch points
35 identify maximum intermediate objects or operations on the
45 pathway to both the house and house with the chimney.

5 In building a house, boards and nails are primitives,
the house is the completed task. But there are intermediate
complexity objects such as framed up walls and windows that
are useful. Why? Essentially, the branch points in the
10 technology graph to a family of objects or objectives
5 identify intermediate complexity polyfunctional
objects/operations - polyfunctional in the sense that
multiple end objectives can be reached using the intermediate
object/operation.

15 But there is a further subtlety. The maximum
10 intermediate branch point might have only a single way
onwards to construct the house, and a single way to construct
the house with the chimney. If, instead, a point a few steps
20 before the last branch point is considered as the
15 intermediate complexity object' operation, there may be
thousands of ways to reach the house and to reach the house
with the chimney. If so, then achievement of either the house
25 or house with the chimney will be robust in the face of
attrition of parts and machines. In short, in a manufacturing
20 context, such intermediate objects are superb to stockpile,
and cost no more than stockpiling the maximum complexity
intermediate objects. In an operational context, the analogue
30 of intermediate polyfunctional objects is intermediate
polyfunctional operation- which retain flexibility to
25 robustly achieve a variety of alternative objectives.

35 In short, technology graphs are the proper mathematical
framework to identify robustly achievable sequences of tasks
to subgoals, alternative subgoals, and final goals.

40 The second approach to the present invention generalizes
30 from Lego world via use of object oriented programming such as
the use of Java objects. In Java, an "engine block",
"piston", and "carburetor" objects are characterized by "is
a", "does a", "needs a", "uses a" features. With proper
search engines, the engine block and piston can "know" that
45 35 the piston fits into the cylinder hole to create a completed
cylinder. In effect, the Java objects are a generative
grammar of parts and transformations of parts that are

5 complements and substitutes, that yields the technology graph
of all objects constructable from those initial parts.

10 In the context of operations, the appropriate set of
objects will include the primitive moves of which battle
5 agents and agents are capable, together with the
corresponding "is a", "does a", "uses a", "needs a" match
features. One essential aim of the present invention is to
establish a set of primitive objects and operations that
15 yields an initial modestly sophisticated technology graph for
the space of battle operations of Red and Blue forces.

20 Given a technology graph, and a specification of objects
or objectives, or a sequence of subobjectives leading to a
final objective, the task of searching the technology graph
for robust pathways is the next serious problem. In general,
15 we propose to use "ant algorithms" and other reinforcement
learning algorithms, to find "optimal robust" pathways to a
sequence of sub-objectives.

25 There are two major issues to be confronted next. First,
we may have a multiplicity of measures of effectiveness
rather than a single measure. Thus, if we use time, attrition
20 and cost as three such measures, we may have no clear
conception of the relative importance of each of these
30 measures to our final purposes. In this case, the natural
solution concept considers "global pareto optimal" surfaces
25 along which it is not possible to improve one of the three
MOEs without making one or more of the remaining MOEs worse.

35 The second major issue is less well known. It appears to
be generically the case that hard combinatorial optimization
problems exhibit a phase transition between a living dead and
30 a survivable regime. We begin with the analogy of a bromine
fog in the Alps. If one is in the fog, one dies. If the fog
40 is higher than Mont Blanc, everyone dies. If the fog is lower
and Mont Blanc, the Eiger and the Matterhorn jut into the
sunlight, then climbers near those peaks can survive. But
45 what if plate tectonics deform the mountainscape? If Mont
Blanc slips into the fog, climbers near that peak will die,
for the distances to any new peaks that now jut into the

5 sunlight are typically large and cannot be reached without
passing into the lethal fog. This "isolated peaks" regime is
also, therefore, the "living dead". Let the fog drift lower
10 and more and more peaks jut into the sunlight. Eventually,
5 when the fog is low enough, it becomes possible to walk
across the Alps always remaining in the sunlight.
Mathematically, this is a phase transition from the isolated
peaks regime to a "percolating web" regime. Note that now, if
15 plate tectonics deforms the landscape, hikers about to dip
10 into the fog can almost always step sideways in one or more
directions and remain in the sunshine. Thus, the percolating
webs regime is survivable in the face of deformation of the
landscape.

20 Deformation of the landscape due to plate tectonics is
15 the analogue of deformation of the payoff landscape in a
space of operations for Blue Force as Red Force alters its
strategies.

25 Several points about this phase transition are
essential. First, it is now well established for several hard
20 combinatorial optimization problems and is likely to be
typical of most realistic hard problems, including military
operations. To be concrete, consider a job shop problem where
30 M machines are to construct O objects. Each object must
"sit" on each machine in some fixed order for some period of
25 time. A schedule is an assignment of objects to machines such
that all objects are constructed. The total time to carry out
35 the schedule is called "Makespan", and is the common measure
of effectiveness. By defining the concept of nearby
schedulers, for example, swapping the order of assignment of
30 an object to a different machine, and by considering
"makespan" as the "fitness" or "cost" of a schedule, a
fitness or cost landscape is achieved. To preserve the image
of the Alps, consider low cost equal to high fitness of a
schedule, then the aim is to find high fitness peaks in the
45 35 space of schedulers.

Short makespan is harder to achieve than long makespan,
hence short makespan is analogous to the bromine fog being

5 high. As makespan decreases from a large - easy to achieve
value, at first there remains a roughly constant number of
schedules, then, at a critical makespan, the number of
10 solutions turns a corner and falls rapidly. This corner is
5 the phase transition from the percolating webs, survivable
regime, into the isolated peaks regime. We stress that a
variety of mathematical measures characterize this phase
transition, including the failure, in the isolated peaks
15 regime, to find percolating webs of solutions, and other
10 measures such as the average Hausdorff dimensionality of the
set of nearby schedules at a given makespan as radius from
that schedule is increased.

20 Furthermore, there is an essential relationship between
the robust constructability discussed with respect to
15 technology graphs and the phase transition. Consider the case
of the job shop problem. If the order in which objects can be
placed on machines can be permuted, the number of conflicting
25 constraints is reduced. Then the fitness peaks in the
schedule landscape become higher and the landscape is more
20 smoothly correlated. In turn, the percolating webs regime
occurs at a higher fitness -hence at a shorter makespan.
Thus, increasing the number of steps that can be permuted
30 shifts the phase transition to the left, to shorter makespan.

But the very point of the technology graph and robust
25 constructability or achievability, is that robust pathways
are sufficiently redundant that there are many nearby
35 pathways to the same objective. In turn, this means that
steps to achieve the objective can be permuted or otherwise
altered. Robustness is therefore associated with reducing
30 conflicting constraints- thereby making the cost landscape in
the space of operations in the technology graph to achieve
the objectives have higher peaks. The survivable regime
occurs at higher values of the measures of effectiveness.

45 In our combined development of the technology graph and
35 battlespace, we propose to implement battle plans to achieve
a sequence of subtasks, as discussed below. The present
invention examines the phase transition in the context of

5 simplified battle plans. Thus, using the technology graph, we
will find large numbers of alternative pathways to each
subgoal. For each pathway, we will measure time, attrition,
10 and cost, our three measures of effectiveness. Therefore, we
5 will build up a profile for each MOE for each subgoal.

Further uses of the concept of the phase transition
should be mentioned. In the absence of attrition by Red
Force, Blue Force should presumably operate near the phase
15 transition but in the survivable regime such that it can cope
10 with alterations in its cost landscape as Red Force alters
that landscape by altering its own strategy. On the other
hand, Red Force is busy trying to destroy Blue Force. We can
20 begin to discover how far "back" of the phase transition,
deeper in the survivable regime, but at worse MOE values,
15 Blue Force should operate in order to remain in the
survivable regime. A first approach is random, Poisson
destruction of Blue Force agents. More difficult, each Red
25 Force strategy will correspond to specific non-random
patterns of loss of Blue Force agents. This requires
20 Investigation.

As the present invention discovers the phase transition,
30 and where Blue force should operate as a function of features
of Red Force strategy, it uses "ant" algorithms that
automatically optimize for the requisite robustness to
25 compensate for attrition, and to confront the persistent need
35 to exploit alternative approaches to old or new subgoals by
graceful redeployment.

The second approach of the present invention is
described next. Consider a World War II sea battle consisting
30 of a convoy and wolf pack. How many fundamentally different
40 ways can this battle unfold? Are there thousands of different
patterns? Hundreds of patterns? Tens of patterns?
Intuitively, but perhaps wrongly, it seems reasonable that
there are a modest number of fundamentally different ways
45 such a battle can unfold. Suppose there were fourteen
35 different patterns. If this is true, then it should be
possible to characterize the strategy spaces of the convoy

5 and the wolf pack and ask for each pair of strategies, where
a strategy is a specific sequence of moves throughout the
whole battle, which of the modest number of outcomes of the
battle happened. If this could be achieved, then the joint
10 strategy space of the convoy and the wolf pack could be
5 partitioned into fourteen phase volumes corresponding to the
different fundamental patterns. Think of these fourteen
volumes as fourteen balloons colored blue, red and white,
15 meaning Blue force wins, Red force wins, and white
10 corresponding to a "draw". The fourteen volumes are arranged
somehow in strategy space. If we are the blue team convoy, we
want to be in a blue balloon as far as possible from a white
or red balloon, subject to our MOEs. If we are in a blue
20 balloon next to a white or red balloon, we surely do not want
15 to cross into one of those neighboring balloons.

In the physicist's sense of "order parameters", it is
reasonable that some particular combinations of essential
25 subtasks characterize the frontiers between two adjacent
balloons. Characterization of those subtasks across the
20 different boundaries of one balloon would characterize the
subgoals that must be achieved to remain in that balloon to
defeated to cross into an adjacent balloon. In short, the
30 present invention characterizes fundamental alternative
outcomes of a battle space so that the resulting phase
25 volumes in strategy space and phase transition surfaces
between those volumes identify critical single or alternative
35 sequences of subtasks that are determinative of the outcome
of the battle.

The present invention characterizes all the primitive
30 moves Red and Blue forces can make, and characterizes
40 "stopping rules" at which the battle will end. Then, the
present invention uses agent based models to play millions of
random battles with random sequences of actions by Red and
Blue forces. This random sample from the Red and Blue Force
45 strategy spaces will sample the strategy space and reveals
35 whether there are a modest number of alternative outcomes of
the battle. The present invention casts each of the millions

5 of battle strategy pairs into the corresponding balloons, and
seek the boundaries between balloons. Even discovering that
such phase volumes exist, their typical layout in strategy
10 space (for example are red and blue balloons randomly
5 intermixed in the joint scraggy space, or do red and blue
balloons typically cluster near one another), and discovery
of the typical the size distribution of the balloons and so
forth would be of deep interest.

15 The third approach will be described next. The third
10 approach is based on optimal command and control structures
on a generalization to a military operational framework of
our current and developing organizational simulation model,
20 which is described in patent application number 09/345,441
filed July 1, 1999, the contents of which are herein
15 incorporated by reference. Our discussion occurs in the
context of: 1) Org-Sim as a platform to study the fitness or
cost landscape represented by an organization's space of
25 operations and need to optimize robust performance.
Associated with this fitness landscape is a framework to
20 understand the statistics of learning curves in
organizations; 2) Org-Sim as a platform to study the
30 relationship between the space of operations, the goals of
the organization, and the optimal organizational-management
structure to achieve those goals; 3) Alternative insights
25 into the requirements for an organization to adapt flexibly
and gracefully as its world changes.

35 Org-Sim is simulates and studies systems such as a gas
refinery which imports raw materials, stores those materials,
processes the raw materials into a variety of products,
30 stores and ships those products into an uncertain market
40 environment.

The Org - Sim platform consists of a set of nodes and
flows. The nodes represent various stages in the assembly and
processing operation such as raw inputs of crude oil, storage
45 35 facilities, cracking towers, subsequent storage facilities,
and so forth. Arrows between nodes depict flows. At the
simplest level, the operations of the refinery is given by,

5 in general, non-linear differential equations representing
the "transfer function" of inputs to outputs at each node.
Already at this simplest level, the platform sets up in the
10 general, hard combinatorial optimization problem for the
5 refinery. How should each node operate, and how should the
transfer functions be altered at each node if that is
feasible, to optimize one or more measures of effectiveness
of the entire refinery.

15 The combinatorial optimization problem sets up the
10 framework for understanding what economists call "learning by
doing". Learning curves in economics record the well known
fact that the cost per unit produced falls by a rough
constant fraction, typically 5% - 10%, for each doubling of
20 total quantity produced. Bios scientists together with
15 outside economists are currently publishing the first
microscopic models accounting for learning curves. It appears
that these curves reflect the statistics of search for
25 improvements in operations over the "cost landscape" for the
alternative ways of operating the plant. The cost landscape
20 is given by all the alternative ways to operate the plant and
a neighbor relation specifying which ways are "near" one
another. The distribution of costs over this high dimensional
30 space is the cost landscape.

The typical features of improvement on such landscapes
25 is that at each improvement step, the number of directions of
further improvement falls by a constant fraction while the
35 amount of improvement is typically a constant fraction of the
previous improvement. Plotting the logarithm of cumulative
improvement tries (hence production runs) on the X axis, and
30 logarithm of cost per unit on the Y axis yields the familiar
near power law learning curve. Thus, Org-Sim embodies the
40 "technological landscape" that must be optimized, and the
statistics of that landscape govern learning curves.

The present invention includes techniques based on
35 Markov random fields to measure sets of nearby "production
45 runs" in the refinery, record their different costs or
effectiveness, in the model or in a real plant, and deduce

5 the statistical structure of the cost landscape. From the
statistical structure and known measures of a modest number
of costs at actual operational points in the space of
10 operations, we can "fit" and interpolate the rest of the
5 landscape at untried points of operation. We believe that
these techniques can be generalized to a space of military
operations as well.

15 Org-Sim, even at this simple level, also embodies the
"mid game chess board" problem. How does one know the value
10 of a mid game board position? Similarly what, exactly, should
the manager of cracking tower 3 do to optimize the
performance of the entire plant? In a military setting, what
subgoals should be set to optimize an overall strategy?

20 The present invention takes two sub-approaches to this
15 issue, one based on reinforcement learning, including "ant"
algorithms. These algorithms scout out alternative pathways
of sequential operations and build up insight into the most
25 successful, including the most robustly successful in the
"technology graph" sense, pathways to the objective.

30 The second sub-approach is based on the concept of the
properly adaptive organization. In general, there is a trade
off between exploitation and exploration. In the landscape
context, exploitation means adaptive search that climbs
steadily uphill to a nearby fitness peak. But in a high
25 dimensional space with very many peaks in a rugged landscape,
that peak is typically a poor one, a poor compromise between
35 the conflicting constraints which create the operational cost
landscape. Exploration constitutes making more dramatic large
experiments, exploring more distant points on the landscape
30 which may be fitter, and more importantly, may lie on slopes
leading to even higher peaks.

40 The present invention includes procedures to measure the
correlation structure of such landscapes, namely how much one
knows about fitness at different distances from any given
45 point whose fitness is known. These landscapes techniques are
described in U.S. Patent application 09/345,441, the contents
of which are herein incorporated by reference. The more

5 rugged the landscape, the more rapidly the correlation falls
off, typically exponentially, with distance. Generically,
when fitness is low, it is optimal to search beyond the
10 correlation length of the landscape where very much fitter
5 positions can be found. If one restricted search to nearby
points, the fact that the landscape is correlated would imply
that their fitnesses cannot be much greater or less than the
current point. By search a long distance away, the search
15 process escapes this correlation constraint. As fitness
10 improves, "long jump" search will typically discard the high
fitness ground achieved, and it is better to search closer to
the current position. This general feature of search on
20 rugged landscapes suggests that optimal adaptation will occur
with wider experimentation early in learning, then settle to
15 refined small variations.

This general feature of optimal search on rugged
operations landscapes, in the military context, should be
25 able to inform both learning by doing in training, and should
have impact on dispersal of authority down the military
20 hierarchy to lower levels with more generalized command by
intent to those lower levels when more wide ranging adaptive
exploration is required.

To study optimal management structure as a function of
the task the organization faces, and a function of the
25 current fitness of the organization, Org-Sim instantiates a
second level: Management. Each node and flow is under the
35 control of a direct line manager. Managers report to high
managers in a definable hierarchy. Each manager is
characterized by features such as line of sight, experience,
30 authority and a decision queue. Line of sight refers to the
number of nearby nodes that manager has information about.
Experience is modeled by allowing more experienced managers
to run, off line, more simulations of the "plant" before
making a decision. Authority is central. Authority allows a
45 manager at a given level to act as follows: If the manager
believes, based on his simulations of the organization that a
change in operations will reduce performance, he does not do

5 it. If he believes that the change in operations will
increase performance up to a given limit, the limit of his
authority, he may carry out such a change. If the expected
improvement exceeds that limit, he bucks the decision
10 upstairs to the next higher manager. Managers have decision
5 queues, so, if overloaded, some decisions will not be made in
a timely way. Information may be degraded passing up and down
the chain of command.

15 The Org-Sim framework inclusive of a space of operations
10 and reconfigurable management structure allows us to
investigate optimal management structure as a function of the
goals of the organization, the structure of the set of
processes leading to those goals, the resultant fitness
20 landscape in the space of operations, and the rate of change
15 of those goals as the external environment changes.

In a number of settings with hard combinatorial
optimization problems, the optimal balance between
25 exploration and exploitation appears to occur in an "ordered
regime" near a phase transition to chaos. In general,
20 adaptation by altering the operations in one part of an
organization create the requirement to alter operations in
nearby parts of the organization to accommodate the initial
30 change. Thus, "avalanches of changes" can arise. In the
ordered regime, alterations in the operation of one part of
25 the organization propagates no, or at best, a few small
avalanches. The organization is "too rigid". In the chaotic
35 regime, an alteration at any point typically unleashes huge
avalanches that spreads throughout much of the organization.
Indeed, the size of the large avalanches scale linearly with
30 the size of the system. At the phase transition between the
40 ordered and chaotic regime, many small avalanches and
relatively few large avalanches propagate through the system.
The size distribution of the avalanches is a power-law, with
a finite cut off that appears to scale as roughly a square
45 root of the size of the system.

5 In several environments we have found that organizations
poised in the ordered regime near this phase transition do an
optimal job of optimizing a fixed hard combinatorial
10 optimization problem in a space of operations, and do an
5 optimal job at the same time of adaptively tracking a
deforming operations environment.

The present invention determines optimal command
structures in the context of our simplified battlespace
15 model. Part of the puzzle of command by direction is
10 precisely our finding that, even with full information, many
hard optimization problems are better solved by breaking the
system into coevolving subunits, each selfishly pursuing its
20 own goals, even at the partial expense of other subgroups in
the organization. This selfish behavior assures that some of
15 the conflicting constraints in the optimization problem are
ignored some of the time, and prevents the system becoming
trapped on poor local fitness peaks that are poor
25 compromises. Indeed, it is just in this setting that we have
found that, for simple problems with relatively simple smooth
20 few peaked landscapes, a single commander performs best, but
that as the problem space becomes more rugged and
30 multipeaked, it is best to break the system into coevolving,
selfish "units" or "patches", whose sizes need to be
carefully tuned such that the entire system is in the ordered
25 regime near the phase transition to chaos.

Part of the puzzle with respect to direction by plan is
35 the need to set a sensible sequence of subgoals. It is not
clear how a complex battle unfolds without such statements of
subgoals and the capacity to alter them in a coordinated way.
40 On the other hand, it appears that experience shows that such
elaborate plans tend to be out of date as soon as the battle
actually starts. This suggests that we try to combine our
unfolding understanding of robust, reliable, flexible,
survivable operations, in the technology graph sense above,
45 35 as a battle unfolds and coadaptation by Red and Blue Forces
occurs, with an attempt to understand what mixture of command
by direction, by plan, and by intent work most effectively in

5 which unfolding situations. Our own preliminary prejudice is
that optimum survivable performance requires operation in the
flexible survivable regime of the technology graph, which
then requires the military organization to be in the ordered
10 5 regime near the edge of chaos in order to learn rapidly how
to achieve changing operational plans and objectives in a
rapidly unfolding and confusing battlespace.

15 While the above invention has been described with
reference to certain preferred embodiments, the scope of the
10 present invention is not limited to these embodiments. One
skill in the art may find variations of these preferred
embodiments which, nevertheless, fall within the spirit of
the present invention, whose scope is defined by the claims
20 set forth below.

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Claims

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Claims

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1. A method for adaptive command and control
5 comprising the steps of:
defining a plurality of subtasks;
determining one or more of said subtasks that
causally effect one or more fundamental outcomes wherein said
15 fundamental outcomes comprise winning outcomes and losing
outcomes; and
determining values for said order parameters to
achieve a winning one of said fundamental outcomes.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/25398

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G06F 17/60

US CL : 705/7, 8, 9

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 705/7, 8, 9

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONEElectronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WEST

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,734,890 A (CASE et al.) 31 March 1998, col. 6, line 55 thru col. 7, line 15, and col. 9, line 53 thru col. 11, line 40.	1
X, P	US 5,963,910 A (ULWICK) 05 October 1999, col. 5, line 36 thru col. 8, line 43.	1
A	US 5,041,972 A (FROST) 20 August 1991, entire document.	1
A	US 5,182,793 A (ALEXANDER et al.) 26 January 1993, entire document.	1

☐ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

* Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance		
"B" earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubt on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means		
"P" document published prior to the international filing date but later than the priority date claimed	"A"	document member of the same patent family

Date of the actual completion of the international search
28 DECEMBER 1999Date of mailing of the international search report
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